CHAPTER 4

PROPELLER TURBINES

4-1. GENERAL USE.

a. Propeller type units, operating at higher speeds and at heads less than 100 feet, have generally replaced Francis turbines. Fixed blade units generally operate over a head range of 6 to 120 feet while adjustable blade units operate up to 250 feet. They have fewer blades than the Francis runner has buckets and consequently do not require as close a spacing of trash rack bars.

b. Fixed blade propeller units are best suited to a narrow range of outputs due to peaked efficiency curves. Kaplan units have adjustable blades which can operate under reduced heads while maintaining good power outputs, have high part gate and overgate efficiencies and can be made responsive to changes in wicket gate opening.

c. Fixed blade propeller units are appropriate where operation will be at or near constant load with small variations in heads. Capital cost will be 25 percent less than adjustable blade units for operation under the same conditions.

d. While adjustable blade units meeting the same conditions could be of smaller diameter and possibly operate at a higher speed, they also have higher runaway speeds and require a lower setting or submergence of the blades.

4-2. SPECIFIC SPEEDS.

a. A general discussion of specific speed is presented in paragraph 2-1. The usual range in specific speeds is from 82 to 205 for fixed blade propeller type units and 90 to 220 for the adjustable blade propeller type (Kaplan). The number of blades will vary from four to eight depending on the range in head, specific speed, and setting.

b. Care must be taken when using specific speed values to insure that they are being correctly used. The best efficiency horsepower at rated head for a fixed blade propeller turbine is matched to 90 - 95 percent of the generator KW rating. The horsepower equivalent of the KW rating is used in calculating the rated specific speed, the blade angle or tilt of the blades being selected to best suit the project requirements. The rated output of a Kaplan turbine is usually matched with the KW rating of the generator at rated head near full gate horsepower at maximum blade angle. The horsepower equivalent of the rating is used in calculating the rated specific speed.

c. A number of existing propeller turbine installations have been examined to develop some general rules for the preliminary selection of specific speed with respect to head. This information has been summarized in the form, $N_s = K/H^{1/2}$, and is presented on Figure 3 of Appendix C. The normal range in heads and associated K values for four, five and six blade runners shown on the curve sheets are recommended for use in determining the first value of N_s. A preliminary value for speed (N) is then calculated from the formula:

$$N = \frac{N_s H^{5/4}}{HP^{1/2}}$$

4-3. <u>MODEL TEST CURVES.</u>

a. Typical performance hill curves developed from model tests, covering both fixed and adjustable blade propeller turbines are shown in Appendix D, Section III. These curves follow the same format as that adopted for the Francis turbine designs (refer to paragraph 3-3a). Pertinent dimensions of the turbine parts and water passages, expressed as a ratio to D_{TH} are shown in Tables 4 and 5, and Figure 5 of Appendix C.

b. In the fixed blade design the inclination of the blades or blade angle dictates the capacity of the unit. However, increases in the blade angle are accompanied by reduction in the peak efficiency. This generally dictates a compromise depending upon the requirements of the project. Model test curves for an adjustable blade turbine having the same number of blades and approximately the same pitch ratio can be helpful in evaluating the effect of change in blade angle on performance, bearing in mind that the smaller hub diameter of the fixed blade turbine will result in some increases in power and efficiency over an adjustable blade turbine of the same runner diameter and number of blades. The pitch ratio is the ratio of the blade length to blade pitch (L/T). This ratio is generally referred to the blade periphery where the blade pitch is equal to the circumference generated by the blade tip divided by the number of blades. Critical sigma can be greatly affected by blade design and blade area, and ample blade area is necessary to keep sigmas within acceptable limits.

4-4. PRELIMINARY DATA FOR FIXED BLADE TYPE.

a. The fixed blade hill curves shown in Appendix D are based on designs that were developed to satisfy specific requirements. Their respective specific speeds at the point of maximum efficiency are: 141 (Figure FB1, Appendix D.) 119 (Figure FB2) and 106 (Figure FB3). Referring to Figure 3 of Appendix C it may be noted that these designs are ideally suited for heads of 32, 57 and 88 feet, respectively. They may be used for other rated head conditions with the precaution that the calculated speeds and runner throat diameters will be at variance with normal Corps practice. In the lower head range this error tends to produce larger, slower speed units, whereas, in the upper head range it tends to produce smaller, higher speed units.

b. If the user is chiefly interested in the size and speed of the unit, the following approximation will produce results more consistent with normal Corps practice. For rated conditions, compute the speed using the method presented in paragraph 4-2c. The peripheral speed coefficient can be estimated from the relationship:

$$\phi_{TH} = 0.089\, N_s^{0.58}$$

The runner throat diameter is calculated through the equation:

$$D_{TH} = \frac{1838\, \phi_{TH}\, H^{1/2}}{N}$$

c. The following procedure is used to compute prototype data from the hill curves in Appendix D.

(1) Pick off HP_1 at desired ϕ_{TH} and efficiency. This point will generally coincide with the maximum efficiency. Determine D_{TH} from the equation:

$$HP = HP_1 \left(\frac{D_{TH}}{12}\right)^2 H^{3/2}$$

$$D_{TH} = \frac{12}{H^{3/4}} \left(\frac{HP}{HP_1}\right)^{1/2}$$

(2) Calculate N from the equation:

$$N = \frac{1838\ \phi_{TH}\ H^{1/2}}{D_{TH}}$$

(3) N must be adjusted to the nearest synchronous speed.

(4) Readjust ϕ_{TH} and repeat steps (1) - (3), if required.

(5) Check performance required at other heads. Computed performance full gate horsepowers should be at least 2 percent higher than the required horsepower to allow for governing and variations such as manufacturing tolerances.

(6) The next step is to determine the setting by computing HP_1 for the required horsepowers, picking off from the sigma curves the corresponding value of critical sigma and solving for H_s in the formula:

$$\sigma_c = \frac{H_b - H_v - H_s - \text{Safety}}{H}$$

(7) Usually it is necessary to investigate three synchronous speeds in order to arrive at the most overall economic speed.

4-5. PRELIMINARY DATA FOR ADJUSTABLE BLADE TYPE.

a. The adjustable blade hill diagrams shown in Appendix D are also based on designs that were developed to satisfy specific requirements. The precautions noted in paragraph 4-4a, also apply to these curves. One requirement that generally dictates this type of unit is a widely varying head. In most of these cases the maximum capacity of the units is required at a rated head considerably lower than maximum head. For this reason the rated ϕ_{TH} is picked to the right of optimum ϕ_{TH}. Since most designs are capable of sustaining good efficiencies up to about 32 degrees blade angle, the rated conditions are generally associated with the on-cam performance at this blade angle. However, other over-riding requirements such as restricted submergence or efficiency may dictate that the rated conditions be referred to other blade angles. As the associated point for rated conditions is moved to the right away from optimum ϕ_{TH} the on-cam HP_1 for fixed blade angles increases, which provides for a smaller, higher speed unit. This advantage is generally offset by slightly reduced efficiency and higher critical sigma.

b. The method described in paragraph 4-4b may be used for approximating the speed and runner throat diameter for the adjustable type by using the following empirical relationship for ϕ_{TH}:

$$\phi_{TH} = 0.049\ N_s^{0.695}$$

c. The step by step procedure for computing prototype data through the hill curves in Appendix D is identical to the procedure described in paragraph 4-4c (1)-(7) with the following exceptions. A preliminary value of HP_1 may be obtained at the intersection of 32 degree blade angle curve and the following ϕ_{TH} values: 2.1(4 blades), 1.7(5 blades) and 1.5(6 blades). The prototype horsepower to be associated with this value of HP_1 will generally correspond to the generator rating. These rules may be varied to suit the specific requirements of the user.

d. Foundation conditions may determine the setting, and require modifications in speed, diameter and vertical height of the draft tube.

e. The selection of the appropriate adjustable blade turbine is more complex than for other turbines and requires much more work in arriving at a satisfactory solution. The range in operating heads may require the preliminary selected value of ϕ_{TH} to be increased. The requirement for a higher efficiency at generator rating may require the selected ϕ_{TH} to be decreased, while an acceptable lower efficiency would permit the ϕ_{TH} to be increased. The horsepower requirements at minimum head may require a change in speed, runner throat diameter and ϕ_{TH}. The value of critical sigma may require a change in HP_1 which would affect the runner diameter and require a change in speed and/or ϕ_{TH}. The effect of all these ramifications on the cost of the turbine, generator and powerhouse structure must be fully considered in making the final selection.

4-6. <u>SETTING OF RUNNER BLADES.</u>

a. Overall plant efficiency is dependent on all portions of the water passages from forebay through the tailrace. The turbine manufacturer is generally responsible for design from the turbine casing inlet to the discharge of the draft tube subject to such limiting dimensions imposed by other considerations and made part of the turbine specifications.

b. The model test information included in Appendix C includes the principal model dimensions of the semi-spiral or spiral casing, draft tube and runner dimensions.

c. The following dimensions are necessary for inclusion in the turbine specifications as limiting dimensions:

(1) Elevation of the center line of distributor.

(2) Elevation of the low point of draft tube floor.

(3) Horizontal distance from center line of unit to end of the draft tube.

(4) Limiting dimensions and elevations of water passages.

d. The formula shown in 4-4 c. (6) is used to calculate the setting of the runner blades. The datum for defining H_s is described in 2-3 b. The value of critical sigma, σ_c, is obtained from the model test curves at the HP_1 corresponding to the rated output. Depending on the value of sigma, H_s may be negative or positive, although it is usually negative for propeller units. Refer to paragraph 2-3.

e. A safety factor must be added to the calculated values of H_s as previously discussed under Paragraph 2-3 c., and

$$H_s = H_b - H_v - \sigma_c H - \text{Safety}$$

f. When using manufacturer's model curves, the manufacturer's safety factor should be carefully considered in determining the setting of the runner. One manufacturer recommends a safety factor equal to 0.2 D_{TH} + 0.7 H, where D_{TH} and H are in feet. This safety factor does not take into consideration the pre-welding of stainless steel on the low pressure side of the blades to mitigate the removal of metal from the surface of the blade by cavitation. Considerable judgment is required in determining the setting of a turbine with consideration for the number of units to be installed, the method of operation and tailwater elevations for initial and ultimate conditions.

4-7. SEMI-SPIRAL AND SPIRAL CASING, AND DRAFT TUBES.

a. The turbine manufacturer is responsible for the design of the water passages from the entrance to the turbine casing inlet to the discharge of the draft tube. Design conditions and limitations, such as velocity at the inlet of the semi-spiral casing, velocity at the discharge of the draft tube and setting the width of the semi-spiral casing should be set by the Corps. These conditions may also include the exit dimensions of the draft tube including the width and number of piers, and lower than normal distances from the center line of the distributor to the bottom of the draft tube and from the center line of the distributor to the roof of the semi-spiral casing.

b. Deviations from strictly homologous water passages may also affect runaway speed, thrust, critical sigma as well as design of moving parts.

c. Procedures based on model laws and model and prototype tests are necessary to the study and selection of equipment, however, they need to be augmented by skills and judgment acquired by experience.

d. For comments regarding spiral casing see paragraph 3-5.

4-8. RUNAWAY SPEED.

a. The runaway speed of the prototype turbine is determined from model tests by running the model at the various gate openings and blade angles for the full range of model RPM (N_1) or ϕ_{TH} to maximum RPM or ϕ_{TH} at minimum values of efficiency and power and extending the curves to zero.

b. As runaway speed is affected by sigma it is also necessary to run sigma versus runaway N or ϕ_{TH} for a range of gate openings and blade angles.

c. Prototype maximum runaway speed is given by the following:

$$(1)\quad N_{max} = \frac{1838\ \phi_{TH}\ H^{1/2}}{D_{TH}},\ \phi_{TH} = \text{max value}$$

or

$$(2)\quad N_{max} = N_1 \left(\frac{D_m}{D_{TH}}\right) H^{1/2},\ N_1 = \text{max value}$$

d. Restricting minimum blade angle and/or maximum gate opening is a means by which runaway speed can be reduced.

e. When the blade angle is restricted, the turbine will operate at reduced efficiency throughout the lower range of output.

f. When the blade angle is restricted, the outer edge or tip of the blade is required to be machined to the contours of the discharge ring with the blades locked in a position corresponding to the minimum angular position of from 14 to 20 degrees with 16.5 degrees being the usual minimum angular position specified. While restricting the blade reduces the flexibility of operation and the efficiency of the turbine at horsepowers below the blade angle restriction, it decreases the maximum runaway speed and improves the efficiencies at and above the blade angle restriction with the greatest increase being in the range of the lower heads. Restricting the blade angle has made it possible to design generators for installations where otherwise it would be impracticable to design generators to withstand the higher overspeeds. When units with restricted blade angles are operated as "spinning reserve" or motoring as synchronous condensers, the energy taken from the system is greater than it would be if the blade angle were not restricted; however, the economics are invariably in favor of restricting the blade angle.

4-9. DRAFT TUBE LINERS.

Draft tube liners should extend a distance equal to at least one discharge diameter of the runner below the point of attachment to the bottom ring.

4-10. AIR ADMISSION.

a. Fixed blade turbines require the installation of air valves connected to the wicket gate mechanism to control the air which must be admitted to the center of the runner cone or hub, the same as for Francis units. A check valve must be installed if the tailwater will be higher than the elevation of the valve or if a tailwater depression system is used.

b. Adjustable blade turbines require large automatic air inlet valves, fitted with dash pots to open on sudden load rejection in order to break the water column upon the gate closure. The air valve must also act as a check valve to prevent the outflow of air or water.

4-11. SLANT AXIS ADJUSTABLE-BLADE TURBINES.

a. The Corps of Engineers has used axial-flow adjustable-blade turbines of the slant (inclined) axis type in three low head projects. Engineering studies indicated a considerable savings in the first cost of these projects. Due to problems with these units, operation and maintenance costs have been high. Also, considerable down time has resulted from turbine problems. For these reasons, consideration of slant axis units should be limited to sites where small units are required and there is an economic advantage.

b. The first installations designed by the Corps of Engineers were for the Ozark and Webber's Falls Projects, both on the Arkansas River. (Rated head - 21 feet. Head range 17 to 34 feet). Each turbine was set at an angle of 12 degrees to the horizontal and drives through a 33,800 horsepower speed increaser a 20,000 KW generator. The size of the turbine was limited by the horsepower of the speed increaser.

c. Subsequent progress in design has permitted a direct connection between turbine and generator, thereby eliminating the need for a speed increaser. This design has been adopted for the Harry S. Truman Project (Kaysinger Bluff) pump turbines which have their shafts inclined at an angle of 24 degrees. Each unit is rated 42,400 horsepower when operating as a turbine at a net head of 42.5 feet and the range in heads is from 41 feet to 79 feet. These are adjustable five blade units and are capable of operating as a pump at a range in pumping heads from 44 to 55 feet. The size of the pump-turbine was limited by the physical size of the generator-motor that could be installed, maintaining the required concrete dimension between the generator housing and the top of the draft tube.

4-12. SAMPLE CALCULATIONS. The basic calculations for typical installations are included in Appendix E.